WHAT IS THE ROLE OF THE INNER MAGNETOSPHERE DURING SUBSTORMS?

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Abstract. Session five of the ICS-4 was devoted to the question "What is the role of the inner magnetosphere during substorms"? There were nine oral papers and nine poster papers presented in this half-day session. The papers ranged very broadly and many touched on several aspects of substorms in the inner magnetosphere. Because of the importance of storms in the inner magnetosphere an number of papers also considered storm-substorm relationships. Here we have grouped the papers of session five into five areas: (1) Auroral Substorms and the Inner Magnetosphere, (2) Thin Current Sheets and Substorm Injections, (3) Ion Composition in the Inner Magnetosphere, (4) Plasma Sheet and Inner Magnetosphere Coupling, and (5) Neutral Atom Imaging. We review the presentations as they were given at the conference, put them in the context of the session, and present selected highlights.

1. Introduction

It is widely agreed that the inner magnetosphere plays an important and active role in substorms and many papers throughout the conference touched on this question. However, this summary concerns itself only with the papers presented in session five and their relation to our overall understanding of substorms and inner magnetospheric processes.

What is the "inner magnetosphere"? Definitions are generally a matter of perspective. The inner magnetosphere must certainly be in the region of closed magnetic field lines. It includes the plasmasphere, the ring current, and the stabally-trapped radiation belts. But how far out does it extend – particularly on the night side? A practical definition might be based on spacecraft orbits. Geosynchronous orbit at approximately 6.6 RE is generally considered to be in the inner magnetosphere. Since highly-stretched, "tail-like" magnetic fields [e.g. *Kaufmann,* 1987*; Pulkkinen,* 1996] and plasma sheet particle populations [e. g. *McComas et al., 1993]* are routinely measured at geosynchronous orbit a practical definition of the "inner magnetosphere" must also include the night side, near-Earth plasma sheet.

2. Auroral Substorms and the Inner Magnetosphere

In recent years there has been a growing awareness that the inner magnetosphere is the location of many important substorm processes. Indeed there it is still argued by some scientists that the inner magnetosphere is the region where substorm onset occurs and that substorm signatures observed in other regions are a consequence of an inner magnetospheric instability. The cause and location of substorm onsets, however, was the subject of session 2 of ICS-4 and the reader is referred to those papers for further discussion.

It is generally agreed that the inner magnetosphere is the region where extremely thin and strong current sheets form, where the substorm current wedge forms, where substorm injections occur, where Pi2 pulsations are measured, and it is the region of the magnetosphere to which auroral field lines map [e.g. *Elphinstone et al.,* 1991; *Kennell*, 1992; *Reeves et al.,* 1996; *Samson et al.,* 1992]. In session 5 these mappings were frequently discussed. *Arykov et al.* specifically examined the mappings of the *Ostapenko and Maltsev* [1997] field model in the region 3-10 RE. Their model uses dipole tilt, Dst, Kp, IMF B_Z, and solar wind pressure as inputs. In addition to confirming the mapping of the auroral zone to the inner magnetosphere they developed approximate formulas for the magnetic foot points as a function of the above five parameters.

The relationship between the AE and PC indices was examined by *Takalo and Timonen*. They found and number of close relationships but also some striking differences in the behavior of the two indices. While the power spectra of the two indices are quite similar and both exhibit significant diurnal variation, the structure function of AE drops off rapidly after two hours while for the PC index it decreases only gradually. They found that the AE index could be predicted from the PC index with an 88% correlation coefficient but that the standard cross correlation peaked with delay times of 2-2.5 hours and that reliable predictions could only be made for times shorter than that. Therefore the size of the polar cap may be a good short term predictor of substorm activity.

Yoyama and Kamide examined the relationship between Dst and the auroral boundary index (which is based on DMSP electron precipitation data). They found that the auroral boundary moves equatorward both during substorms

and during the main phase of storms but that during storms the auroral boundary reaches its lowest latitude about one hour before the minimum Dst is measured.

Additional information on energetic particle precipitation into the auroral zone can be obtained from the POLAR PIXIE experiment which provides global x-ray images of the auroral zone. In a statistical study of PIXIE images *Petrinec et al.* investigated the relationship between auroral x-rays and the average location of the visible auroras as well as deriving empirical relationships with solar wind parameters and geomagnetic indices.

3. Thin Current Sheets and Substorm Injections

During substorms the magnetic field and particle distributions in the inner magnetosphere undergo distinct changes. During quiet times the cross-tail current is comparatively weak and relatively far from the Earth so the transition from dipole-like to tail-like fields is gradual. During the growth phase the plasma sheet thins, the current sheet strengthens and both move Earthward. Very stretched, tail-like magnetic fields are observed in the vicinity of geosynchronous orbit and there can be a relatively abrupt transition from dipole-like to tail-like fields. At the same time that the plasma sheet moves earthward bringing higher fluxes of thermal plasma to the midnight region energetic particles are frequently observed to decrease well below their pre-growth phase levels. While the flux of energetic particles is decreasing a strong field-aligned, or cigar-like, pitch angle distribution develops.

Along with the stretching of the magnetic field, the energetic particle dropout and development of a cigar-like pitch angle distribution is one of the most reliable indicators of substorm growth phase in the inner magnetosphere. At ICS-4, *Toivanen* presented a model of this process based on a combination of magnetic field models, particle drift models, and CRRES energetic particle data. He found that during the growth phase particles lose energy as they drift through the evolving fields near local midnight but that the amount of energy loss is greater for $90°$ pitch angle particles than for more field-aligned particles which could account for both particle dropouts and the development of cigar-like anisotropies.

Pulkkinen considered the development of highly stretched magnetic fields during the growth phase. In previous work *Pulkkinen et al.* [e.g. 1996] have modeled the highly-stretched growth phase magnetic fields by modifying the Tsyganenko magnetic field models. Here she compared GOES data at geosynchronous orbit with GEOTAIL data in the middle tail and found that the thin current sheets of the growth phase begin to develop at both location essentially simultaneously and very quickly after the IMF turns southward. This observation highlights both the global development of large-scale current systems and also the speed at which the magnetosphere responds to solar wind energy input.

During the substorm expansion phase the magnetic field dipolarizes and energetic particle fluxes in the inner magnetosphere not only return but typically surpass their pre-growth-phase levels. *Reeves* discussed these substorm injections and considered how they fit into recent understanding of the overall substorm process. He argued that the signatures of the injection are the near-Earth signature of fast convective flows from the tail. The fast flows have been well-observed and modeled recently and are one of the major changes in substorm physics. In his view, the breaking and diversion of the flows around the dipole inner magnetosphere cause strong inductive magnetic fields, produce field-aligned currents that form the current wedge, and also launch a compressional wave that further energizes and transports particles into the dipole regions. This work stressed that the source of the substorm instability does not have to be in the inner magnetosphere in order for the inner magnetosphere to be an active participant in the substorm process – again emphasizing the global, coupled nature of the substorm.

4. Ion Composition in the Inner Magnetosphere

Additional insight into the effect of substorms on the inner magnetosphere can be gained by examining ion composition measurements. Recent satellite missions, including CRRES, AMPTE, and POLAR, have provided an unprecedented database for understanding ion composition changes during storms and substorms. While three papers tackled this subject, the effect of substorms on ion composition in the inner magnetosphere remains controversial.

Two studies of ion composition changes during storm-time and non-storm-time substorms were presented by *Daglis* and *Grande et al.* There is general agreement that the oxygen content of the inner magnetosphere, and the ring current in particular, is substantially higher during storms. The storm-time ring current energy density can sometimes be dominated by oxygen [*Daglis*]. Because O^+ and H^+ have different charge exchange lifetimes and different wave-particle interactions the oxygen content has clear implications for the evolution of the ring current and hence of the storm-time magnetic field.

The role of substorms in producing composition changes is less certain. *Daglis* argued that storm-time substorms are not isolated and that earlier substorms in a sequence may precondition the ionosphere and draw more O^+ up the magnetic field lines so that during storms the ionosphere will supply much more plasma to the magnetosphere than it would during an isolated substorm.

While not disagreeing with *Daglis, Grande et al.* provided a slightly different perspective. They showed that, although storm-time substorms were statistically more likely to have high oxygen content, the correlation between composition and Dst was weak. In examining the correlations between a number of different parameters they found that the best predictor of the composition measured

after a substorm onset was the composition measured before the substorm. This result appeared to hold both for storm-time and non-storm-time substorms. They concluded that substorms had little effect on inner magnetospheric composition.

While part of the controversy may lie in the subtlety of the analysis methods much of the blame must be placed on the lack of consensus on the general topic of storm-substorm relationships [*Tsurutani et al.,* 1997]. If one accepts the premise that storms are more than simply a collection of substorms then the single most important global condition during storms is probably the existence of considerably stronger electric fields and global currents. It may be those global conditions that determine the ionospheric coupling and outflow while it is the substorms, and specifically substorm injections, that energize those particles and bring them into the inner magnetosphere from the plasma sheet.

Watanabe et al. investigated the ionospheric ion outflow near the Transverse Ion Energization (TIE) region which lies near the polar cap boundary at altitudes above about 2000 km. Using Akebono data they found that that outflow of light ions (H^+ and He^+) typically occur equatorward of the TIE and correspond with the classical polar wind while oxygen outflow can be a major component of outflow further poleward. During magnetically active times the outflow regions systematically move equatorward which could certainly be important for determining how much oxygen can get into the inner magnetosphere.

Peterson et al. examined convection from the plasma sheet to the inner magnetosphere by analyzing events measured by the POLAR satellite. They found that dusk side passes very commonly showed broad energy bands in O^+ and H^+ that increase in energy with increasing L. At $L \approx 4$ they typically have central energies of 10, 50, and occasionally 100 keV. Using a simple model of plasma sheet convection with constant drift velocity and conservation of the first adiabatic invariant, μ, they found that the observed ion distributions were consistent with a single spatial and temporal distribution of source populations in the tail. The implication of this work is that inner magnetospheric composition can be strongly coupled to plasma sheet source distributions. The primary difference between substorm and non-substorm times in their model is simply the rate of convection (assuming μ is conserved) which implies that the condition of the plasma sheet may be the most important factor in determining input of particles to the inner magnetosphere during substorms.

While Peterson's model qualitatively accounts for the observed ion distributions it is admittedly simplistic. *El-Alaoui et al.* presented a far more sophisticated model of plasma sheet particle dynamics based on a hybrid MHD-kinetic approach. They have previously shown that non-linear and non-adiabatic processes are typical of the mid-tail but for the first time extended the simulations to conditions of southward IMF. The results of the simulations allow detailed analysis of the possible particle distributions and the contribution from different magnetospheric and ionospheric sources to those distributions but the implications for macroscopic substorm effects in the inner magnetosphere will require further investigation.

5. Plasma Sheet and Inner Magnetosphere Coupling

The coupling between the plasma sheet and the inner magnetosphere has important implications beyond those related to ion composition. It was generally agreed that the coupling is weakest during quiet times when convecting particles from the plasma sheet either do not have access to the inner magnetosphere or are on open drift trajectories and are therefore a temporary population. *Reeves* argued that it is the time-dependent, spatially localized, inductive electric fields that allow previously untrapped energetic particles to become quasi-stably trapped during substorm injections. During storms a similar process must operate but with one significant difference. The stronger cross-tail and inductive electric fields during storms probably allow the significantly deeper penetration necessary for ring current formation.

This view was supported by *Kozyra et al.* who showed that, in addition to composition, the temperature and density of ions in the plasma sheet can have a significant effect on the formation of the ring current. They showed the results simulations of ring current development run with and without enhanced plasma sheet densities and found that enhanced plasma sheet densities can increase ring current strength by at least a factor of three. While ionospheric outflow may be an important source for enhanced plasma sheet density during storms [*Daglis*] there is also evidence that the density in the solar wind plays a dominant role.

Additional insight into storm-time substorm injections and their role in ring current development came from *Korth et al.* Their long-term study of CRRES data as a function of L and time clearly shows that differing types of geomagnetic activity can produce different ring current responses. They found that the ring current is enhanced at all energies from 10 to 300 keV, over distances L = 2–7, and for all measured ions (protons, helium and oxygen). They further presented evidence that a sequence of substorms is necessary to produce a symmetric ring current while individual substorms cause only a partial ring current.

While most studies of the storm-time ring current use the Dst index as a measure of ring current strength a novel approach using magnetogram inversion techniques (MIT2 code) was presented by *Mishin and Urbanovich*. They compared the total energy input from the solar wind, the total power dissipated in the ring current Q_{DR}, and the total power dissipated in the ionosphere Q_I and found that the ratio of Q_{DR}/Q_I during substorms varied considerably but could be as high as three. They further suggested that the ratio might be controlled by the length of the magnetotail which, if verified, would have surprising implications for understanding the storm-substorm relationship.

Flowers also investigated solar wind energy input to the magnetosphere and found that, while solar wind energy input did not appear to determine the size or magnitude of a substorm, there was a clear correlation with substorm repetition rate. They also separated substorms by dipole tilt and found that the two sets of substorm had quite different features. While the results were quite striking the use of CRRES data introduces an ambiguity between selections based on season and dipole tilt and will require confirmation using less biased data sets.

5. Neutral Atom Imaging

A new tool for understanding substorm physics is neutral atom imaging. To date most neutral atom measurements have been Energetic Neutral Atom, ENA, measurements. ENAs are produced when ions in the inner magnetosphere are neutralized by charge-exchange collisions with low-energy atoms from the geocorona. Once neutralized, the particle motion is unconstrained by the magnetic field so particles from the inner magnetosphere can be detected remotely from any other part of the magnetosphere and analyzed to produce an "image" of the source populations.

Orsini and Candidi presented an overview of neutral atom imaging results to date including results from ISEE, GEOTAIL, ASTRID, and POLAR. They also described some of the extensive modeling that is being done in order to apply ENA measurements to substorms and storms. ENA measurements are particularly well suited to measurements of the ring current both because they provide a true global measurement and because they are directly produced by charge exchange and thus are unaffected by changes in other current systems.

But ENA measurements also reveal the physics of substorms. *Reeves*, speaking for *Jorgensen et al.*, showed sequences of images from POLAR that clearly show both substorm injections and the westward drift of the injected energetic ions. They showed that the timing of "ENA bursts" and in situ measurements of ion injections measured at geosynchronous orbit were essentially simultaneous. They also illustrated an imaging technique that synthesizes multiple substorm images into a single "composite" substorm image with much higher spatial and temporal resolution than is otherwise possible. In addition to providing dramatic visual images, neutral atom imaging provides a global context for the relatively sparse measurements from satellites.

7. Conclusions

The International Conferences on Substorms provide an opportunity to re-assess the sate of substorm research every few years. ICS-4 was particularly satisfying because of the obvious and significant progress that had been made in the two years since ICS-3. This is particularly true of our understanding of processes in the inner magnetosphere.

ICS-4 was more, however, than an opportunity to present results, review accomplishments, and congratulate one another. New collaborations were formed, new ideas were discussed, and each answered question suggested more questions still in need of answers. This collection of papers provides some record of the content and accomplishments of our session on The Role of the Inner Magnetosphere but some of what was accomplished at ICS-4 will not be apparent until we re-assess a few years hence at ICS-5 in St. Petersburg, Russia.

Papers Presented in Session 5

Arykov, A. A., Yu. P. Maltsev, and A. A. Ostapenko, Effect of substorms and storms on magnetic mapping.

Daglis, I. A., Ion composition in the inner magnetosphere: Its importance and its potential role as a discriminator between storm-substorms and non-storm-substorms.

El-Alaoui, M., M. Ashour-Abdalla, J. Raeder, L. A. Frank, and W. R. Paterson, Modeling the plasma populations of the near-Earth plasma sheet during substorms.

Flowers, N. J. Magnetospheric energy input and its effect on repetition rates and magnitudes of substorms in subsequent dissipation.

Grande, M., C. H. Perry, A. Hall, Y. Kamide, R. Nakamura, J. Fennell, and B. Wilken, Statistics of magnetospheric composition during storm-time and quiet-time substorms.

Korth, A., C. Mouikis, and R. H. W. Friedel, Dynamics of the outer radiation belt during storms/substorms: Measurements from CRRES.

Kozyra, J. U., M.-C. Fok, V. K. Jordanova, and J. E. Borovsky, Relationship between plasma sheet preconditioning and subsequent ring current development during periods of enhanced cross-tail electric field.

Mishin, V. M., and V. D. Urbanovich, On the substorm-storm relationship problem.

Orsini, S., and M. Candidi, Charge-exchange processes in the inner magnetosphere and energetic neutral atoms.

Peterson, W. K., K. J. Trattner, O. W. Lennartsson, H. L. Collin, T. I. Pulkkinen, D. N. Baker, P. K. Toivanen, T. A. Fritz, J. F. Fennell, and J. L. Roeder, Multi-component O^+ and H^+ distributions observed at L<6 before and after a large isolated substorm.

Petrinec, S. M., J. Mobilia, D. L. Chenette, M. A. Rinaldi, and W. L. Imhof, PIXIE observations of the auroral energetic electron precipitation region.

Pulkkinen, T. I., Coupling of inner tail and midtail processes prior to substorm onset.

Reeves, G. D., M. G. Henderson, A. M. Jorgensen, and H. E. Spence, Energetic neutral atom (ENA) bursts measured by POLAR and their relationship to magnetospheric substorms.

Reeves, G. D., New perspectives on substorm injections.

Takalo, J., and J. Timonen, On the relation of the AE and PC indices.

Toivanen, P. K., On the role of the inductive electric fields in the inner magnetosphere

Watanabe, S., K. Katsuyama, H. Fukunishi, A. W. Yau, E. Sagawa, and T. Abe, Akebono/SMS observations of plasmaspheric refilling and source of magnetospheric plasma during magnetically active periods.

Yokoyama, N. and Y. Kamide, Storm/substorm effects on the size of the auroral belt.

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